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Recognition memory for low- and high-frequency filtered emotional faces: Low spatial frequencies drive emotional memory enhancement, whereas high spatial frequencies drive the emotion-induced recognition bias

Published: 17 December 2021

Volume 50, pages 1000–1014, 2022 | How to cite

Article type: Research Article

Keywords: EMF | SF | Emotion | Face perception | Memory

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Abstract

This article deals with two well-documented phenomena regarding emotional stimuli: emotional memory enhancement and the emotion-induced recognition bias. Furthermore, it investigates how these effects are mediated by spatial frequencies that—a clear-cut distinction of spatial frequencies is hypothesized that for natural scenes, binocular vs. foveal emotion perception and whether high-and low-frequency filtered emotional faces can be mediated by means of spatial frequencies. Participants (N = 105) viewed neutral faces of both genders, half of which were low-frequency or unaltered (i.e. phase-scrambled) stimuli. Subsequently, two spatial frequencies are presented to give a primary cue for the influence of emotion on attention and judgment. Subsequently, participants had to rate their recognition confidence and perceived emotion. We found a memory advantage for emotional faces and for LSF this emotion-induced recognition bias, to a lesser or different recognition experiment. Participants completed incidental learning tasks with high- (HSF) and low- (LSF) spatial frequency filtered emotional faces and neutral faces. The results of the surprise recognition were directly a clear memory advantage for emotional stimuli. More importantly, the emotional memory enhancement was mediated by spatial frequencies, with a memory advantage for low-frequency filtered faces. Moreover, we found a memory advantage for emotional faces, but only for LSF emotional faces, a clear-cut effect, whereas the emotion-induced recognition bias was found only for HSF stimuli. We discuss our findings in terms of both the traditional accounts of differential processing of low- and high-SF and SF information and a stimulus-based account. The double dissociation in the results favors the latter account—that is, an adjustment in terms of differences in the characteristics of HSF and LSF stimuli.

Fig. 1

Figure 1

Schematic depiction of the stimulus filtering. Applying a high-pass frequency filtered stimulus (HSF) on the left and a low-pass frequency filtered stimulus (LSF) on the right

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For example, as a neutral stimuli, Vuilleumier et al. (2003) compared stimuli filtered for differential amount of spatial frequencies (SF) and found that fearful faces, in contrast to neutral faces, elicited more activation in the amygdala for unaltered and spatial frequency. Amygdala activity was stronger for emotional faces for neutral faces, and both HSF and LSF conditions during a gender categorization task, whereas there was no differential response for HSF faces. Hence, the amygdala as an emotion-related brain area seems to respond strongly to emotional information only when this information contains low spatial frequencies, and thus, the amygdala response to HSF faces is not modulated by emotion. Similarly, Vuilleumier et al. (2003) and Pourtois et al. (2005) and Vuilleumier et al. (2003) and Pourtois et al. (2005) and Vuilleumier et al. (2003) and Pourtois et al. (2005) and

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Low frequencies

A 3 (Emotion) × 4 (Task) MANOVA for repeated measures yielded a main effect of emotion (see Table 2 for the inferential statistics). Remarkably, this effect was present across all four tasks, $Fs(2, 55–65) > 4.30$, $ps < .019$, $\eta_p^2 > .125$. The first contrast (joy/fear vs. neutral) was significant and associated with a difference between *d'* for emotional faces and *d'* for neutral faces of $M = .32$ ($SD = .82$), which corresponds to an effect size of $d_Z = .39$ (i.e., an effect just below "medium size" according to Cohen, 1988). Again, this effect held for all four tasks, $Fs(1, 56–66) > 6.23$, $ps < .016$, $\eta_p^2s > .085$. Thus, as hypothesized, the emotional LSF stimuli were associated with better recognition than were the neutral LSF stimuli. The second contrast (joy vs. fear) was significant as well, suggesting that memory performance for fearful LSF faces was slightly better than performance for happy LSF faces. The effect was, however, very small, $M = .13$ ($SD = .87$, $d_Z = .15$), and significant only for one task (i.e., regional provenance), $F(1, 66) = 5.34$, $p = .023$, $\eta_p^2 = .076$; $F(1, 56) = 3.69$, $p = .060$, $\eta_p^2 = .062$, for emotion, and $Fs < 1.43$, $ps > .236$, for the remaining tasks. Again no significant interactions involved task. Thus, recognition memory was relatively comparable for happy and fearful faces.

High frequencies

A 3 (Emotion) × 4 (Task) MANOVA for repeated measures yielded a main effect of emotion as well (see Table 2 for the inferential statistics). Again, the first contrast (joy/fear versus neutral) was significant. Thus, the emotional memory advantage was also present for HSF stimuli. However, as already shown by the interaction effect in the overall analysis, this effect was significantly smaller than the corresponding effect for LSF stimuli. The difference between *d'* for emotional faces and *d'* for neutral faces was $M = .14$ ($SD = .75$), which corresponds to an effect size of $d_Z = .19$ (i.e., a "small" effect according to Cohen, 1988). Moreover, it was significant only for the gender task, $F(1, 61) = 5.67$, $p = .020$, $\eta_p^2 = .085$; $Fs < 3.24$, $ps > .076$, for the remaining tasks. The second contrast was not significant. Again, no significant interactions involved task. Thus, in line with our hypotheses, the emotional memory advantage in the high spatial frequencies was relatively small and did not hold across tasks.

Assuming unequal variances: d_a instead of d'

As we outlined above, we conducted alternative analyses of sensitivity by using d_a (with $s = 0.8$) instead of *d'*. Table 7 shows the inferential statistics for the 2 (Frequency) × 3 (Emotion) × 4 (Task) MANOVA for repeated measures with Task as a between-subjects factor. As can be easily seen by comparing Table 7 with Table 2 (i.e., the analyses using *d'* as the dependent variable), everything was essentially the same except one detail: The difference between happy and fearful low-frequency faces disappeared if we assumed unequal variances (with $s = 0.8$). This result leads us to conclude that the above-reported small difference in recognition memory between happy and fearful faces was not reliable; rather, recognition memory was comparable in both the happy and fearful face conditions.

Recollection and familiarity

The remember/know/guess data are shown in Table 8; Table 3 shows descriptive statistics for the indices of recollection and familiarity. A 2 (Index: recollection vs. familiarity) × 2 (Frequency) × 3 (Emotion) × 4 (Task) MANOVA for repeated measures, using the recollection and familiarity indices as dependent variables, yielded a significant Index × Frequency × Emotion interaction, $F(2, 245) = 3.76$, $p = .025$, $\eta_p^2 = .030$, which was not further moderated by task, $F < 1$, indicating that recollection and familiarity were influenced by both emotion and spatial frequency. In parallel to the recognition results, the interaction was mainly due to the first contrast (i.e., neutral vs. fear/joy), $F(1, 246) = 4.64$, $p = .032$, $\eta_p^2 = .019$; $F < 1.06$ for the moderation by task. The second contrast was nonsignificant, $F(1, 246) = 2.54$, $p = .113$, $\eta_p^2 = .010$, $F < 1$, for the moderation by task. Thus, recollection and familiarity differed depending on emotionality and frequency. To investigate these differences in more detail, we analyzed low and high spatial frequencies again separately.

Table 3 Mean familiarity and recollection values as a function of frequency and emotional expression

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Low frequencies

As can be seen in Table 3, the 2 (Index) × 3 (Emotion) × 4 (Task) repeated measures MANOVA for low frequencies yielded that the first contrast of the emotion effect was dominantly familiarity-based [$F(1, 246) = 5.38$, $p = .021$, $\eta_p^2 = .021$, for the Index × Emotion interaction]. However, the contrast (emotion vs. neutral) was significant for familiarity, $F(1, 246) = 20.19$, $p < .001$, $\eta_p^2 = .076$, as well as for recollection, $F(1, 246) = 8.30$, $p = .004$, $\eta_p^2 = .033$.

High frequencies

The corresponding analysis for high spatial frequencies showed that the first contrast was numerically more based on recollection differences [$F(1, 246) < 1$ for the Index × Emotion interaction]. The contrast was significant for familiarity, $F(1, 246) = 7.73$, $p = .006$, $\eta_p^2 = .030$, for high/familiarity, as well as recollection, $F(1, 246) = 24.83$, $p < .001$, $\eta_p^2 = .092$, for high/recollection.

Thus, familiarity as well as recollection contributed to the emotional memory advantage in both LSF and HSF stimuli, albeit to different degrees. The LSF emotional memory advantage was primarily due to familiarity; the (relatively small) HSF emotional memory advantage was primarily based on recollection. From the perspective of emotion memory, one might have expected that the LSF emotion advantage should also be driven by recollection. However, it is not clear which exact encoding and mnemonic processing stages are in which way impacted by the spatial frequency manipulation. Thus, the observed outcome might be plausibly explained given the specific filtering conditions. We will discuss the possible reasons for the outcome in the discussion.

Response bias

Mean values of the response bias *c* are given in Table 4. Positive values indicate a more conservative criterion, negative values a more liberal response criterion. To examine whether response criteria differed between the emotional and neutral stimuli, we conducted a 2 (Frequency) × 3 (Emotion) × 4 (Task) MANOVA for repeated measures, with Task as a between-subjects factor and all other factors as within-subjects variables, using *c* as the dependent variable (see Table 5 for the inferential statistics). The analysis yielded main effects of spatial frequency and emotion, as well as a significant interaction of emotion and spatial frequency (which was not further moderated by task). Thus, response bias differed depending on frequency and emotion. Again, we analyzed high and low spatial frequencies separately to further disentangle the interaction.

Table 4 Mean response bias scores (c) as a function of frequency, emotional expression, and task (*SD* in parentheses)

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Table 5 Inferential statistics for response bias (c) for the overall analysis and the analysis of low and high frequency stimuli

Full size table ›

Low frequencies

For low spatial frequencies, a 3 (Emotion) × 4 (Task) MANOVA for repeated measures yielded a main effect of emotion, which was solely due to the second contrast (which was not further moderated by task).[9] The response criterion for negative faces was significantly more conservative than the one for positive (and than that for neutral) faces. However, we should not put too much weight on this result; it is the only one reported in this section that can potentially be reduced to differences in categorization performance (see Appendix 2).

High frequencies

For high spatial frequencies, a 3 (Emotion) × 4 (Task) repeated measures MANOVA yielded a main effect of emotion—which, however, was due solely to the first contrast: The response criterion for emotional faces was significantly more liberal than the one for neutral faces.

Discussion

The present study provides the first evidence that emotional memory enhancement can indeed be manipulated by means of spatial-frequency filtering. Across all tasks, low spatial frequency emotional faces elicited significantly larger emotional memory enhancement than high spatial frequency faces, which only showed a small enhancement. In addition, the emotion-induced recognition bias was also influenced by the spatial frequency manipulation. Although high-frequency emotional faces were associated with a more liberal response bias, fearful low-frequency faces were associated with a more conservative bias. The effects were not moderated by type of encoding task. That is, we cannot attribute the result to the demands of any special task (e.g., that a given task is better supported by high or by low frequencies, thereby creating different depths of encoding for the different frequencies). In the remainder of this Discussion, we will discuss the two phenomena—emotion-enhanced memory and emotion-induced recognition bias—separately.

Emotion-enhanced memory

The larger sensitivity advantage (relative to neutral faces) for emotional low-frequency faces than for emotional high-frequency faces held across tasks and for different alternative dependent variables (i.e., *d'*, d_a with $s = 0.8$, and *Pr*) and can therefore be considered a robust finding. In addition, in the analyses of *d'* (as well as *Pr*), a small fear-over-happy advantage was found for low-frequency faces (but not for high-frequency faces). However, this result is more equivocal since it was not confirmed in the alternative analyses using d_a as the dependent variable and it was not found for all tasks; we will thus refrain from further elaborating on this effect.

Although differences in emotional processing provide the most straightforward explanation for the observed results, there is a potential caveat: A critical reader might think that the Emotion × Frequency interaction might have been caused by differences in recognition performance—specifically, by comparable levels of recognition for emotional LSF and HSF faces, but worse recognition of neutral LSF faces than of neutral HSF faces. However, this notion (1) cannot explain why neutral faces in particular should show this difference, and (2) it completely ignores the main effect of recognition for LSF versus HSF faces. LSF and HSF facial stimuli differ with regard to the level of distinctiveness, with HSF stimuli providing more details for encoding a distinctive representation and more details to act as a more distinctive retrieval cue. Slightly different levels of overall recognition performance for HSF and LSF stimuli can thus be expected a priori. Consequently, the only way to adequately interpret the Emotion × Frequency interaction is to describe it as a larger recognition advantage for emotional stimuli in the LSF condition than in the HSF condition.

Given the main effect of frequency, a second caveat is to presume a ceiling effect for emotional HSF faces. However, the overall level of recognition performance is far from ceiling even for HSF stimuli. Moreover, the different tasks were associated with slightly different levels of overall recognition performance but the presence versus absence of a recognition advantage for emotional HSF faces across tasks does not vary with the overall level of recognition performance (see Fig. 2). Thus, we take the Emotion × Frequency interaction to indicate a genuinely larger effect of emotional content in LSF than in HSF stimuli.

This pattern of results suggests that spatial-frequency filtering can indeed be used to selectively engage processes involved in the interaction of emotion and memory. The findings corroborate the importance of low spatial frequencies for emotion processing (Laeng et al., 2010; Vuilleumier et al., 2003) and extend these findings from perception and judgment to memory. By means of additional categorization data (see Appendix 1), we could rule out that differences in the emotional categorizability of the filtered faces could account for the memory effects.

Importantly, the results cannot be attributed solely to fast and early perceptual processes, given the relatively long (i.e., 5-s) presentation time at encoding. Returning to our critical discussion from the introduction, we see the following routes of interpretation. First, we can interpret the results in line with the existing literature on frequency-filtered stimuli. That is, we assume that LSF and HSF stimuli differentially engage emotion-related processing paths, with LSF stimuli activating these paths more than HSF stimuli. However, this interpretation requires the additional assumption that the differential engagement is not constrained to the first fractions of a second but sustained over a longer period. If we take this stance, it is interesting to note that positive and negative low-frequency emotional faces were associated with a comparable recognition advantage, suggesting no difference in the processing of positive and negative valence. Given that our stimuli were carefully matched on arousal, this result implies that the previously observed influence of valence on emotional memory (i.e., a greater recognition advantage for negative vs. positive items, relative to neutral items) may reflect differences in stimulus arousal rather than differences in underling memory processes (for this argument, see also Mather & Sutherland, 2009).

Second, we can take a step back and consider other differences between LSF and HSF facial stimuli (apart from the triggering of different pathways) that could account for the results. Indeed, the following argument can, in principle, explain the results without referring to different processing paths: Earlier, we explained the main effect of frequency by referring to differences in distinctiveness between high- and low-frequency faces. In an abstract sense, faces can be characterized by *x* features (on average) that distinguish the exemplars within the set of HSF faces, and by *y* features (on average) that distinguish the exemplars within the set of LSF faces, with *x* being larger than *y*. Everything else being equal, a larger feature vector, that is, a more distinct pattern, promotes recognition success—hence the main effect of frequency. If we assume that (1) emotional connotation is one of the features, and (2) that the presence of a feature (i.e., "looks happy" or "looks fearful") is represented in memory but not its absence (i.e., "neutral-looking" is not a feature—take a beauty spot as an analogue), we can easily explain the emotion × frequency interaction: Neutral faces "miss" one feature and are thus less distinct than emotional faces—hence the general recognition advantage of emotional faces. Finally, the relative importance of a distinguishing feature directly determines differences in recognition success: The ratio $1/y$ is larger than the ratio $1/x$—hence, the larger emotional advantage for LSF than for HSF stimuli.

This explanation fits to the analyses of familiarity and recollection as well. The emotional memory advantage in the low spatial frequencies was primarily based on familiarity, whereas the small emotional memory advantage in the high spatial frequencies was to a larger extent due to recollection. The reduced stimulus distinctiveness of LSF stimuli might have prompted fewer associations at encoding (e.g., "She reminds me of my school friend Jane." or "His nose looks like an arrow.")—in turn, meaning that fewer details may have been available at retrieval to warrant a "remember" response. Thus, it seems plausible that the emotional memory enhancement in the low spatial frequencies was primarily driven by familiarity. Alternatively, the "blurry" perceptual impression of LSF faces might have decreased confidence of the old/new judgments, thereby leading to a shift in response criterion toward a "know" rather than a "remember" response. The resulting remember/know/guess response pattern might thus also indicate differences in memory strength rather than differences in the underlying memory processes (cf. Wixted & Mickes, 2010).

The explanation of the Emotion × Frequency interaction in terms of distinctiveness does not refer to different affective processing paths for both high- and low-frequency faces. It does not even refer to affective processing of emotional faces at all. Certainly, this explanation cannot account for the memory advantage of emotional stimuli in general, given the vast amount of evidence regarding the impact of specific emotion-related processes on memory (i.e., physiological influences and different neuronal processing). However, the distinctiveness notion is able to explain the memory advantage of emotional faces in behavioral studies, since it rests on the assumption that an emotional expression constitutes a recognition-relevant feature whereas neutrality does not. If the explanation accounts for such results, it can potentially be tested by creating encoding contexts that switch the asymmetry (i.e., that neutrality is encoded as a feature, emotion not). For example, imagine an encoding context that presents happy and neutral faces as depicting guests of a party. Then, "neutrality" of a facial expression might be better encoded than the emotional "happy" expression, which would be considered the default in this context (see Schmidt, 1991, regarding the assumption that unusual or unexpected items are perceived as more distinct; McDaniel & Geraci, 2006, for a review). Regarding the present study, this would mean that distinctiveness and diagnosticity are the driving factors underlying the present results, not a specific link between low spatial frequencies and emotion processing.

Emotion-induced recognition bias

Although not the central focus of our experiments, our analyses revealed that spatial frequencies not only had an impact on emotional memory, but also moderated the effect of emotion on the response criterion. For high frequencies, emotional faces (i.e., positive and negative ones) were associated with a more liberal response criterion than neutral faces. This result corresponds with an *emotion-induced recognition bias* that is typically found with negative words but has also been reported with faces (Johansson et al., 2004; but see Windmann & Chmielewski, 2008) and positive words (Windmann & Chmielewski, 2008). For low frequencies, however, the result did not replicate. (Indeed, negative LSF faces were associated with a significantly more *conservative* response criterion than were positive faces. However, as already indicated in the Results section, we should not put too much weight on this detail since it can potentially be reduced to differences in categorization performance (i.e., it is difficult to recognize whether a face is fearful or neutral, leading to a shift in response criterion; see Appendix 2).

The more liberal response criterion for emotional HSF faces (than for neutral ones) is only a small effect. However, its size matches the corresponding (nonsignificant) effect found for faces by Windmann and Chmielewski (2008). There are three main explanations of the emotion-induced recognition bias (see, e.g., Windmann & Chmielewski, 2008), two of which attribute it to genuine emotion processing. First, the *executive-control account* (Windmann & Krüger, 1998) claims that there is an asymmetry between "old" and "new" responses: An "old" response is the preactivated response tendency that is (often) executed on the basis of automatic processes; a "new" response is the result of more controlled processes. Emotional stimuli (especially threatening ones) tend to interrupt or impair ongoing controlled processes, and it follows that the tendency to give the preactivated "old" response increases. Second, according to a variant of the *memory bias account*, "emotion circuits in the brain…boost the activity of currently activated sensory and mnemonic representations in such a way that emotional stimuli appear clearer and more vivid than nonemotional stimuli" (Windmann & Chmielewski, 2008, p. 764). This clarity and vividness is misattributed to familiarity, thus increasing the rate of "old" responses.

For two reasons, both accounts cannot explain why, in our results, the HSF stimuli in particular are associated with the recognition bias. First, although it may seem plausible that LSF faces triggered emotional processes to a larger degree than HSF faces, given the long presentation duration, it would seem far-fetched to claim the opposite. Second, if the recognition bias result is explained with reference to genuine emotional processes, consequentially (though not necessarily) the emotion-enhanced recognition performance should be explained with reference to emotional processes as well. Doing so, however, creates a dilemma because one would need to assume stronger emotional processing of HSF faces in the case of the recognition bias, but stronger emotional processing of LSF faces in the case of emotion-enhanced recognition performance.

However, a third account of the recognition bias—the *semantic cohesion* explanation (Maratos et al., 2000)—focuses on the fact that the effect has been found most consistently for negative word stimuli. Typically, negative words in a study have stronger semantic interrelations. Therefore, semantic priming processes within old and new words can make negative words appear more familiar, inducing a bias toward "old" responses. Of course, due to its specific focus, this explanation cannot be straightforwardly applied to facial stimuli. However, a reinterpretation of this account might make it applicable. If we assume that the cohesion does not result in priming processes (i.e., a mutual facilitation of old and new negative words), but simply means that there is greater similarity (overlap) in the feature vectors that represent negative word concepts (as compared to positive and neutral ones), we can explain the recognition bias by the process of retrieval confusion: due to overlap, a new negative word has an increased likelihood of activating the feature vector of an old word. This reinterpretation of the semantic cohesion account can, in principle, be applied to our materials as well, if we make the additional post-hoc assumption that happy and fearful HSF faces, respectively, are on average perceived to be more similar to each other than neutral HSF faces (i.e., both might be perceived as expressive, and therefore more similar to each other than to neutral, whereas LSF faces might provide generally fewer associations, as we noted above). However, this assumption remains speculative at present. Further research will be necessary to clarify what underlies the emotion-induced recognition bias in our study. We wanted, however, to highlight that the bias might also be explained by nonemotional processes.

Conclusion

Taken together, our study provides the first behavioral evidence for a differential enhancement of emotional memory due to spatial-frequency filtering. An emotional memory enhancement was consistently observed only for the low spatial frequencies. This is in line with the assumption that these frequencies are important for the automatic activation of emotion-related processes. However, this interpretation in terms of genuine emotion-related differences between LSF and HSF faces can be challenged in several ways. First, the effect was found despite the long presentation duration of stimuli in the encoding phase, which suggests that the impact of spatial frequencies on emotional processing does not necessitate short and fast presentation conditions. Second, the result can potentially be explained in terms of differences in the number of mnemonically relevant stimulus features and resulting differences in item discriminability. Third, a further result—the emotion-induced recognition bias found with HSF but not LSF faces—produces a dilemma if it is interpreted as a genuine emotion effect at the same time as the emotional memory enhancement effect. Thus, the observed results can also be explained by nonemotional aspects related to perception (i.e., distinctiveness, diagnosticity). Clearly, more research is needed to determine whether the observed effects are based on emotion-related processing differences or not. Potentially, the observed results emerge from several underlying processes (emotion-related and not emotion-related ones), which are impacted by manipulation of spatial frequency.

In this regard, we also wish to note several limitations of the present study. At first, it would have been desirable to include a nonfiltered comparison condition. In this way, we could have compared whether recognition memory of spatial-frequency-filtered stimuli is generally different from the recognition memory performance of unfiltered stimuli. The present results only allow us to compare HSF and LSF stimuli. Second, the specific encoding tasks created some (although negligible) variability in the results. It would be desirable to control for this variance, for example, by including performance in the encoding tasks as a further control factor. Unfortunately, this was not possible in the present study, because information about age and provenance were not available for the stimuli. Thus, responses in these tasks were arbitrary. Emotion intensity was a subjective judgment. Future studies in this field could include encoding performance as a further factor into the analyses (if the employed tasks provide this possibility) to enhance clarity of results. Furthermore, the inclusion of neuropsychological methods could help to clarify the exactly underling processes (e.g., differential activation of emotion-related brain areas at encoding and retrieval could help to decide, which one of the two alternative explanations is correct). At the present point, we can only speculate about the exactly underlying processes. Whether emotion-related processes or perceptual ones drive the results cannot be determined on the basis of these results alone. Nevertheless, our study can serve as a starting point for research on emotion and memory using frequency-filtered stimuli. It shows that spatial frequencies play a role for recognition memory. If emotion-related processes underlie the present results, this would extend the link of emotion and spatial frequencies to memory; if perceptual processes underlie the present results, our study would provide interesting insights into the emotional memory advantage in general. We thus hope that our study encourages further research in this field.

Notes

1. We have chosen these two specific emotions because of theoretical considerations (e.g., Öhman & Mineka, 2001) and because of empirical evidence that (especially negative) high-arousing emotions might preferably trigger subcortical, emotion-related brain areas (e.g., Mattavelli et al., 2014). More specifically, increased amygdala activation relative to neutral stimuli has not only been observed for BSF (i.e., nonfiltered), but also for LSF fearful faces (Vuilleumier et al., 2003).

2. We have chosen these specific tasks because all of them are based on perceptual characteristics of the face and typically are automatically inferred (i.e., people automatically infer emotion, age, gender, and provenance from a face). Moreover, with regard to gender, emotion, and race, evidence already exists of the diagnosticity of a specific spatial frequency range (e.g., Aguado, Serrano-Pedraza, Rodríguez, & Román, 2010; Fiset, Blais, Gosselin, Bub, & Tanaka, 2008; Harel & Bentin, 2009; Schyns & Oliva, 1999). Thus, by employing different tasks, we could ensure that our results were not driven by the diagnosticity of the specific frequency range.

3. More precisely, we used MATLAB'S fir1 filter (with parameters 50 and 6/100 [low] or 24/100 [high], Nyquist frequency of 100 [i.e., the horizontal plane]) to create a 2-D mask, which was then multiplied with the Fourier representation of the image.

4. An anonymous reviewer correctly pointed out that we did not adjust the root mean square (RMS) contrast, which is a better indicator of perceived contrast (Bex & Makous, 2002). Thus, it could still be possible that differences in contrast contributed to our results. However, first, RMS contrast did not differ across emotion categories within one frequency spectrum, and second, the pattern of observed results would not be predicted from a contrast explanation. Precisely, if RMS contrast had driven the results, one would have expected better recognition and better memory for the high-contrast LSF stimuli, because contrast has been observed to correlate with activity in V1 (Boynton, Engel, Glover, & Heeger, 1996). Moreover, neural responses saturate at medium to high contrast levels. Although the specific contrast–response functions vary across brain areas and specific cells, many neuronal responses are nearly saturated at Michelson contrasts above 0.3 (e.g., V1 and LGN; Sclar, Maunsell, & Lennie, 1990) or at less than 40% RMS contrast (in V1 and fusiform face area (FFA); Yue, Cassidy, Devaney, Holt, & Tootell, 2011). A recent study by Maher et al. (2016) also showed that the FFA already responds to faces at very low contrasts, and that the response does not change with increasing contrast. Thus, it is very unlikely that differences in the RMS contrasts of the stimuli had an influence onto the results.

5. The filler task was a distractor–response binding paradigm (see Frings & Moeller, 2012). In this task, letters were presented as either targets or distractors in a flanker configuration. Thus, the task was cognitively demanding, but not related to emotion.

6. Only $n = 19$ participants across all experiments stated that they had an idea that a memory test was going to be conducted ($n = 4$ in the age task, $n = 7$ in the provenance task, $n = 8$ in the emotion task, and $n = 0$ in the gender task). Moreover, these responses seemed partially due to the demand character of the question. Several participants made further comments like "I guessed it," "Now that I know, I find it not surprising," "It was intuition," and no participant mentioned having explicitly encoded the faces. Therefore, all participants were kept for further analyses. Excluding these participants did not change the results.

7. Thus, we acknowledge the ongoing debate regarding the adequacy of continuous versus discrete models of recognition processes (see, e.g., Kellen, Klauer, & Bröder, 2013; Klauer & Kellen, 2015; and Pazzaglia, Dube, & Rotello, 2013, for recent contributions). Note that the most often used alternative to *d'* and *c*—namely *Pr* and *Br* from double high-threshold theory (Snodgrass & Corwin, 1988)—yielded essentially the same results as *d'* and *c* with our data.

8. One might argue that the remember/know/guess differentiation might be taken as a proxy for confidence ratings. However, Martin and colleagues (2011) compared ROC analyses based on confidence ratings and on remember/know/guess differentiation. The two analyses diverged especially with regard to the ratio *s*: ROC analyses based on confidence yielded values of $s < 1$, whereas ROC analyses based on remember/know/guess yielded values of *s* that did not significantly deviate from 1. Thus, a critic would not be convinced by ROC analyses based on remember/know/guess data.

9. The first contrast interacted significantly with task (see Table 3). This was due to the comparably large variability of the neutral condition across tasks (see Table 2). We refrain from discussing this detail due to its questionable replicability.

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Author note

This research was supported by a grant from the German Research Foundation (DFG, No. MU 1230/19). The authors thank Ulrich Ecker for his helpful comments and Gerit Grabhorn for his support concerning stimulus preparation and filming.

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Appendices

Appendix 1

Table 5 Norm rating data of the images used, taken from Langner et al. (2010) for the FAEIS set and Goeschen et al. (2009) for the EAEIF set

Full size table ↗

Table 7 Inferential statistics for memory performance (p_c) for the overall analysis and the analysis of low- and high-frequency stimuli

Full size table ↗

Table 8 "Remember" and "know" responses to old items (hits) and to new items (as in parentheses) as a function of frequency, emotional expression, and task

Full size table ↗

Appendix 2

All filtered stimuli were presented to a separate sample of participants ($N = 29$) in a forced choice categorization task. Table 9 depicts the mean categorization rates for each emotion and response category, averaged across individuals.

Table 9 Mean categorization rates and mean unbiased hit rates (in percentages) for each emotion category and spatial frequency

Full size table ›

All emotions were clearly recognized above chance (i.e., >33%). Moreover, all emotions except LSF fear were recognized almost perfectly. Fearful LSF expressions were to a certain extent mistaken as being neutral (i.e., there was a conservative response bias for the category fearful). To statistically examine differences between the categorization rates, we calculated the unbiased hit rate (Wagner, 1993) for each participant, thereby considering potential response biases. As is indicated in Table 9, unbiased hit rates for fear and neutral faces are somewhat lower than the original hit rates, due to the fact that neutral faces were sometimes mistaken as fearful or vice versa. The arc sine transformed unbiased hit rates were analyzed in a repeated-measures MANOVA with emotion and spatial frequency as within-subjects factors. This analysis yielded a main effect of emotion, $F(2, 27) = 144.10$, $p < .001$, $\eta_p^2 = .914$, a main effect of frequency, $F(1, 28) = 46.65$, $p < .001$, $\eta_p^2 = .625$, and a significant emotion × frequency interaction, $F(2, 27) = 16.87$, $p < .001$, $\eta_p^2 = .555$. High-spatial-frequency faces were generally better categorized, and happy faces were better recognized than neutral and fearful faces. Although we observed no difference between neutral and fearful faces in the high spatial frequencies, fearful faces were categorized significantly worse, $t(28) = 5.00$, $p < .001$ (i.e., confused with neutral faces) than neutral faces in the low spatial frequency condition.

Thus, the pattern of differences does not mimic the pattern of recognition reported in the Results section. It is therefore unlikely that the memory results can be reduced to differences in categorization accuracy. Nevertheless, to corroborate this claim, we correlated recognition performance (d'), and response bias (c) with categorization performance using items as data units, aggregated over spatial frequency as well as separately for HSF and LSF versions. Aggregated over spatial frequencies, we did not find any correspondence for recognition performance ($r = .00$, $p = .99$) or response bias data ($r = -.07$, $p = .43$). Separate analyses for low and high spatial frequencies yielded insignificant correlations as well ($r = -.15$, $p = .21$, for LSF; $r = .19$, $p = .11$, for HSF). Given the different signs and the insignificance of these correlations, they cannot account for the emotional memory advantage.

However, correlations of the emotion-induced recognition bias with the categorization data indicated that the observed conservative bias in the low spatial frequencies might be due at least partly to categorization difficulty. LSF categorization performance was negatively related to the response criterion ($r = -.23$, $p = .05$). To shed further light on this issue, we conducted a hierarchical multiple regression with response criterion as the dependent variable and two coding variables corresponding to the contrasts neutral versus emotional faces (K1) and happy versus fearful faces (K2) as predictors entered in Step 1 as well as categorization performance in Step 2. In line with the findings reported in the Results section, K2 (but not K1) was a significant predictor in Step 1. In Step 2, however, none of the predictors were significant, which indicates that K2 and categorization performance are mutually redundant. Thus, we cannot refute the argument that categorization performance is responsible for the response bias result. The corresponding correlation for HSF was insignificant and, more important, had a different sign ($r = .20$, $p = .08$). Thus, the more liberal response criterion for emotional HSF faces cannot be explained by differences in recognition.

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Rohr, M., Tröger, J., Michely, N. *et al.* Recognition memory for low- and high-frequency-filtered emotional faces: Low spatial frequencies drive emotional memory enhancement, whereas high spatial frequencies drive the emotion-induced recognition bias. *Mem Cogn* **45**, 699–715 (2017). https://doi.org/10.3758/s13421-017-0695-2

Download citation

Published
17 February 2017

Issue Date
July 2017

DOI
https://doi.org/10.3758/s13421-017-0695-2

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